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LETTER

Disturbance-induced reduction of biomass carbon sinks of China's forests in recent years

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Abstract

Forests play a critical role in mitigating climate change because of their high carbon storage and productivity. China has experienced a pronounced increase in forest area resulting from afforestation and reforestation activities since the 1970s. However, few comprehensive analyses have been made to assess the recent dynamics of biomass carbon sinks in China's forests. This study refined biomass carbon sinks of China's forests based on eight forest inventories from 1973 to 2013. These sinks increased from 25.0 to 166.5 Tg C yr^{-1} between 1973 and 2008, and then decreased to 130.9 Tg C yr^{-1} for the period of 2009–2013 because the increases in forest area and biomass carbon density became slower. About 7% and 93% of this sink reduction occurred in planted and natural forests. The carbon sinks for young, middle-aged and premature forests decreased by 27.3, 27.0, and 7.6 Tg C yr^{-1}, respectively. 42% of this decrease was offset by mature and overmature forests. During 2009–2013, forest biomass carbon sinks decreased in all regions but the north and northwest regions. The drivers for changes of forest biomass sinks differ spatially. More intensive harvest of young and middle-aged forests and snow damage were the major drivers for the decreases of biomass carbon sinks in the east (8.0 Tg C yr^{-1}) and south (19.8 Tg C yr^{-1}) regions. The carbon sink reduction in the southwest region (16.7 Tg C yr^{-1}) was mainly caused by increased timber harvesting and natural disturbances, such as droughts in Yunnan province, snow damage in Guizhou province and forest fires in Sichuan province. In the northeast region, the sink reduction occurred mainly in Heilongjiang province (7.9 Tg C yr^{-1}) and was caused dominantly by the combined effects of diseases, windthrow and droughts. The carbon sink increase was primarily attributed to forest growth and decreased deforestation in the north (10.0 Tg C yr^{-1}) and northwest (2.3 Tg C yr^{-1}) regions.

1. Introduction

Forests play a dominant role in the Earth's terrestrial carbon sinks which retard the atmospheric CO_2 buildup (Bonan 2008, Pan *et al* 2011, Shevliakova *et al* 2013). Two processes are responsible for forest carbon sinks: age-related growth (regrowth) after disturbance and land use change and growth enhancement due to environmental changes (for example, climate, CO_2 and nitrogen deposition) (Hember *et al* 2012, Fang *et al* 2014a, Wu *et al* 2014). The sustainability of forest carbon sinks is greatly affected by the frequency and intensity of large disturbance events and depends on how quickly forests recover their capacity for photosynthesis (Sun *et al* 2012, Huang *et al* 2013).

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Severe and extended forest disturbances reduce ecosystem carbon sequestration, or even switch forests from a carbon sink to a source for a period of time until a carbon compensation point is reached, i.e., net primary productivity (NPP) exceeds heterotrophic respiration. The effects of major disturbances, such as droughts, ice rain, and ice storm on gross primary productivity (GPP) and NPP, have been studied extensively (Huang *et al* 2013, Pei *et al* 2013, Wang *et al* 2014). Recently, many efforts have been made to study the impact of climatic extremes on forest growth and biomass dynamics and reported that drought stress might weaken forest growth and carbon uptake (Peng *et al* 2011, Pei *et al* 2013, Liu *et al* 2014).

Up to 2013, forests in China covered 21.6% of the total national land area and accounted for 5.2% of the global forest area (FAO 2010). Many studies reported that China's forests functioned as a significant carbon sink over the last several decades based on inventory data (Pan *et al* 2011, Zhang *et al* 2013, Fang *et al* 2014b), process models (Tian *et al* 2011, Zhang and Liang 2014), and atmospheric inversions (Piao *et al* 2009, Jiang *et al* 2013). However, the conclusions on the spatial and temporal variations, magnitude, and drivers of this carbon sink are still inconsistent.

Inventory-based studies indicated that long-term net carbon uptake by China's forests is primarily attributed to forest expansion and regrowth driven by intensive afforestation and reforestation continuously conducted since the early 1970s (Fang *et al* 2001, Guo *et al* 2013, Zhang *et al* 2013). Tian *et al* (2011) found that forest expansion contributed about 40% of the carbon sink increase in China's forests between 1961 and 2005. The areas of plantation and natural forests increased by 25.49×10^6 ha and 21.99×10^6 ha in the past four decades, respectively. These two types of forests were estimated to account for 94% of the national total area of forests in China (Yu *et al* 2014). Most of these forests are currently at young and middle ages with high carbon uptake capacities and might act as carbon sinks in the future (Zhang *et al* 2013).

Unfortunately, forests in China were affected by increasing human and natural disturbances in recent years. The latest 2009–2013 national forest inventory reported an increasing timber harvest (Chinese Ministry of Forestry 2014). Meanwhile, droughts, snowstorms, windthrow, insects and disease more frequently hit forests in China than before and consequently impacted their carbon sequestration (Chinese Ministry of Forestry 2009, 2014). For example, in tropical and subtropical regions of China with a monsoon climate, seasonal and interannual variations of precipitation are considerable. Carbon sequestration by forests here decreased substantially under seasonal drought conditions (Sun *et al* 2006). On the basis of modeling analysis, Gu *et al* (2008) indicated that drought caused net ecosystem productivity (NEP) of a subtropical coniferous plantation in southern China to decrease by 63% and 47% in 2003 and 2004, respectively. The carbon-use efficiency (the ratio of NPP to GPP) of this forest decreased after the massive ice storm in early 2008 and returned to normal status at least four years later (Wang *et al* 2014). The drought-induced reduction of GPP, NPP, and NEP of forests in China has been recently reported in several remote sensing-based modeling studies (Zhang *et al* 2012b, Pei *et al* 2013, Liu *et al* 2014).

However, the quantitative response of the national biomass carbon sink of China's forests to both human and natural disturbances is still not clear. Here, we use data from 8 consecutive national forest inventories, in conjunction with a newly refined continuous biomass expansion factor (CBEF) model (Zhang *et al* 2013) to analyze the dynamics of biomass carbon sinks in China's forests for the period of 1973–2013 and explore the possible drivers. The major objectives of this study are: (1) to update forest biomass carbon sinks in China for the period from 2009 to 2013 using the 8th national forest inventory datasets; and (2) to assess the impacts of anthropogenic and natural disturbances on the dynamics of biomass carbon sinks in China's forests over the past decade.

2. Materials and methods

2.1. Forest inventory and field measured data

Two types of data were employed in this study, including national 8 forest inventory datasets compiled by the State Forestry Administration in eight periods (1973–7976, 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008, and 2009–2013) and field biomass measurements at 3543 forest plots across China compiled from literature. Details on these two types of data were described in Zhang *et al* (2013).

Ten types of human activities and natural disturbances were considered here, including afforestation and reforestation, forest logging, fires, diseases, insects, windthrow, snow, landslide, drought, and other disasters. The forest disturbance information was retrieved from the national forest inventory data (Chinese Ministry of Forestry 2009, 2014), including areas undergoing afforestation and reforestation, harvested stand volume, and forest areas affected by different types of natural disturbances.

2.2. Estimation of forest biomass carbon sinks

The biomass of forests was calculated using 8 national forest inventory datasets from 1973 to 2013 and the refined CBEF method (Zhang *et al* 2013). In this study, only forest stand living biomass was calculated, excluding carbon contained in wood products as well as in soils. Since 1994, the canopy coverage criterion of forests in China has been changed from >30% to 20%. The method developed by Fang *et al* (2007) was employed to correct biomass calculated using the inventories prior to 1994.

Since one forest inventory spans about 5 years for the whole country in China, the biomass carbon sink during two consecutive inventory periods was calculated as the change of biomass carbon stocks divided by the interval between their median years.

2.3. Calculation of change rates in forest area and carbon density

The changes of forest area and biomass carbon density drive biomass carbon stock changes (i.e., carbon sinks or sources). Here, we employed the concept of Forest Identity to evaluate the impact of changes in forest area and carbon density on the forest biomass carbon sink in China. The relative annual change rates of forest area and carbon density can be expressed as follows (Fang *et al* 2014a):

$$M = A \times D, \tag{1}$$

$$\frac{\mathrm{d}\ln(M)}{\mathrm{d}t} = \frac{\mathrm{d}\ln(A)}{\mathrm{d}t} + \frac{\mathrm{d}\ln(D)}{\mathrm{d}t}. \tag{2}$$

Let

$$m \approx \frac{\mathrm{d}\ln(M)}{\mathrm{d}t},\ a \approx \frac{\mathrm{d}\ln(A)}{\mathrm{d}t},\ d \approx \frac{\mathrm{d}\ln(D)}{\mathrm{d}t}. \tag{3}$$

Then

$$m = a + d, \tag{4}$$

where M, A, and D are the biomass carbon stock (Tg C), area (ha), and biomass carbon density (Mg C ha^{-1}) at the national level, respectively; m, a, and d are their annual change rates (% yr^{-1}), respectively. The years used here to represent forest inventory periods were the median for each time period.

3. Results

3.1. Biomass carbon sink dynamics of forests in China

The national total carbon sink of forest biomass increased with fluctuations, from 25.0 Tg C yr^{-1} during 1977–1981 to 130.9 Tg C yr^{-1} during 2009–2013, averaging 80.6 Tg C yr^{-1} over the four decades in China (table 1). About 37% (29.4 Tg C yr^{-1}) and 63% (51.1 Tg C yr^{-1}) of this sink were contributed by planted and natural forests. As expected, planted forests have functioned as a persistent carbon sink since the early 1980s driven by area expansion and forest growth (i.e., increasing carbon density) owing to intensive national afforestation and reforestation programs, with a peak of 59.9 Tg C yr^{-1} during 2004–2008. Natural forests showed a carbon loss of 28.7 Tg C yr^{-1} during 1984–1988. This was caused largely by timber harvest of productive forests with large carbon stocks and sinks (figures 1(b) and (c)). Although planted forests acted as a carbon sink of 23.6 Tg C yr^{-1}, China's forests overall was a biomass carbon source of 5.1 Tg C yr^{-1} for the period of 1984–1988 (table 1).

Since 1998, the biomass carbon sink of forests increased dramatically, owing to considerable increases in the area and carbon density (table 1) driven by the implementation of the 'Grain for Green' project and improved sustainable management of forest resources and environmental protection initiated in 1998 (Zhang *et al* 2000). However, the total forest biomass carbon sink during the period from 2009 to 2013 was 35.6 Tg C yr^{-1} smaller than that during the period from 2004 to 2008. The biomass carbon sinks of planted and natural forests decreased by 2.5 Tg C yr^{-1} and 33.1 Tg C yr^{-1}, accounting for 5% and 93% of the total reduction, respectively. The decline of forest biomass carbon sinks was due to the decreases in the increasing rates of forest area and biomass carbon density for both planted and natural forests (figure 2(a)). Averaged over the 8th inventory period, the increasing rates of the area and carbon density of national total forests (including planted and natural forests) were, respectively, 1.126% yr^{-1} and 0.868% yr^{-1}. They were considerably smaller than the corresponding values of 1.716% yr^{-1} and 1.144% yr^{-1} during the 7th inventory period. The reduction of the forest biomass carbon sink was mainly caused by the reduction of biomass carbon sinks of young, middle-aged, and premature forests with high biomass carbon sink intensity (figures 1(c) and (d)). The biomass carbon sinks of these three age classes decreased by 27.3, 27.0, and 7.6 Tg C yr^{-1}, respectively. Fortunately, the increases in biomass carbon sinks of mature (17.5 Tg C yr^{-1}) and overmature (8.8 Tg C yr^{-1}) forests as a consequence of accelerated area increment compensated for 42% of sink reduction of young, middle-aged, and premature forests.

3.2. Regional variations of forest biomass carbon sinks

Forest biomass carbon sinks in China showed substantial spatial and temporal variations, ranging from a carbon source of 88.0 Tg C yr^{-1} (3.10 Mg C ha^{-1} yr^{-1}) during 1977–1981 in the northeast region to a carbon sink of 106.4 Tg C yr^{-1} (2.80 Mg C ha^{-1} yr^{-1}) during 1999–2003 in the southwest region (figure 3). Overall, the biomass carbon sinks increased from 1973 to 2013 in all regions but the north region. The largest increase of biomass carbon sink occurred in the northeast region. The very large forest biomass carbon sink in the north region for the period of 1977–1981 was mainly attributable to the significant increase of 375% in forest area here (table S1). Over the study period from 1973 to 2013, the southwest region had the largest average biomass carbon sink of 29.4 Tg C yr^{-1}, followed by the north (22.1 Tg C yr^{-1}), south (17.3 Tg C yr^{-1}), east (14.7 Tg C yr^{-1}), and northwest (4.8 Tg C yr^{-1}) regions. However, forests in the northeast region acted as a biomass carbon source of 7.7 Tg C yr^{-1} caused by deforestation-induced decrease of 21% in forest area (table S1).

Table 1. Forest area, biomass carbon stocks, and carbon sinks for all forests, and planted and natural forests during the period from 1973–1976 to 2009–2013 in China.

Period	All forests				Planted forests				Natural forests			
	Area	Stocks	Density	Sink	Area	Stocks	Density	Sink	Area	Stocks	Density	Sink
	(10^6 ha)	(Tg C)	(Mg C ha^{-1})	(Tg C yr^{-1})	(10^6 ha)	(Tg C)	(Mg C ha^{-1})	(Tg C yr^{-1})	(10^6 ha)	(Tg C)	(Mg C ha^{-1})	(Tg C yr^{-1})
1973–1976	117.12	4111.3	35.1	—	21.58	313.2	14.5	—	95.55	3798.1	39.8	—
1977–1981	116.64	4211.4	36.1	25.0	15.93	276.7	17.4	−9.1	100.71	3934.7	39.1	34.2
1984–1988	124.53	4175.8	33.5	−5.1	23.42	441.8	18.9	23.6	101.11	3733.9	36.9	−28.7
1989–1993	132.16	4521.4	34.2	69.1	26.58	527.4	19.8	17.1	105.58	3994.0	37.6	52.0
1994–1998	132.73	4602.0	34.7	16.1	29.14	654.3	22.5	25.4	103.59	3948.2	38.1	−9.2
1999–2003	142.79	5409.6	37.9	161.5	32.29	813.9	25.2	31.9	110.49	4595.7	41.6	129.5
2004–2008	155.59	6241.8	40.1	166.5	40.00	1113.2	28.0	59.9	115.59	5128.6	44.4	106.6
2009–2013	164.60	6896.3	41.9	130.9	47.07	1400.0	29.7	57.4	117.53	5496.3	46.8	73.5

'—' means no value. Carbon content is converted from biomass using a factor of 0.5.

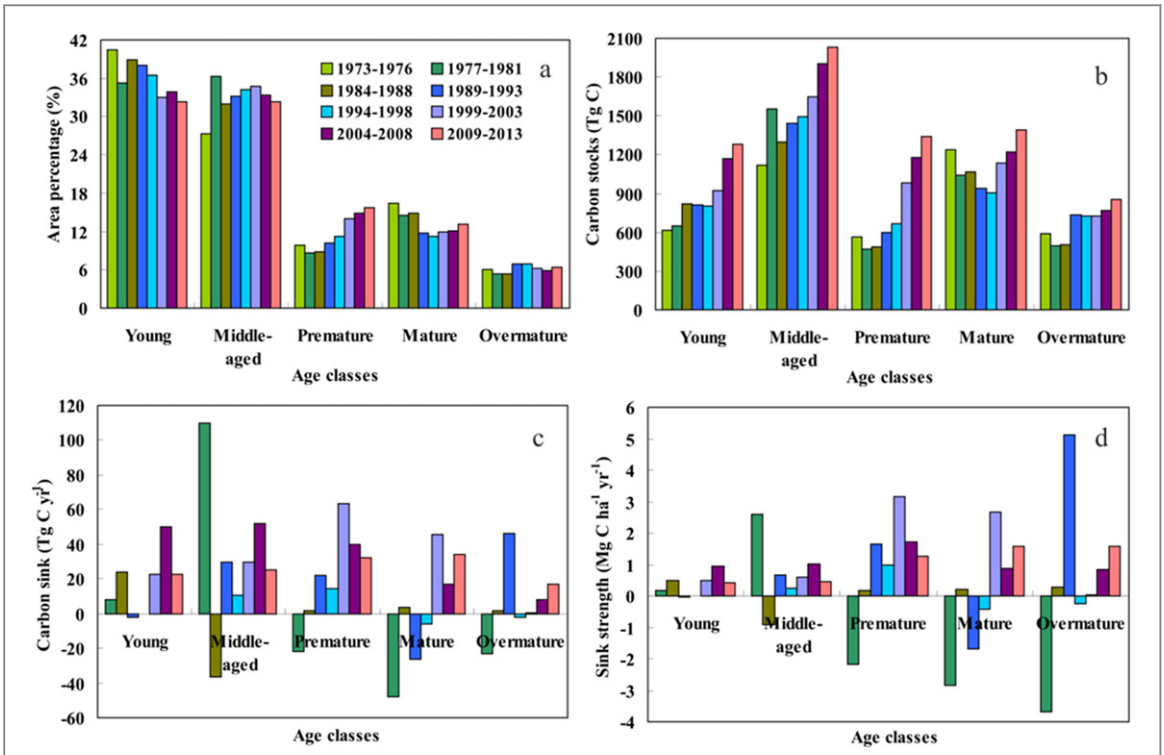

Figure 1. Dynamics in (a) forest area percentage, (b) biomass carbon stock, (c) biomass carbon sink, and (d) biomass carbon sink strength for five age classes (young, middle-aged, premature, mature and overmature) during the period from 1973–1976 to 2009–2013 in China. Premature, mature, and overmature forests were lumped together in the first two inventory periods of 1973–1976 and 1977–1981. We used the area ratios of premature, mature and overmature forests calculated from the inventory during 1984–1988 to divide mature forests into three age classes (premature, mature and overmature) for the periods of 1973–1976 and 1977–1981. Negative values indicate carbon sources, and vice versa.

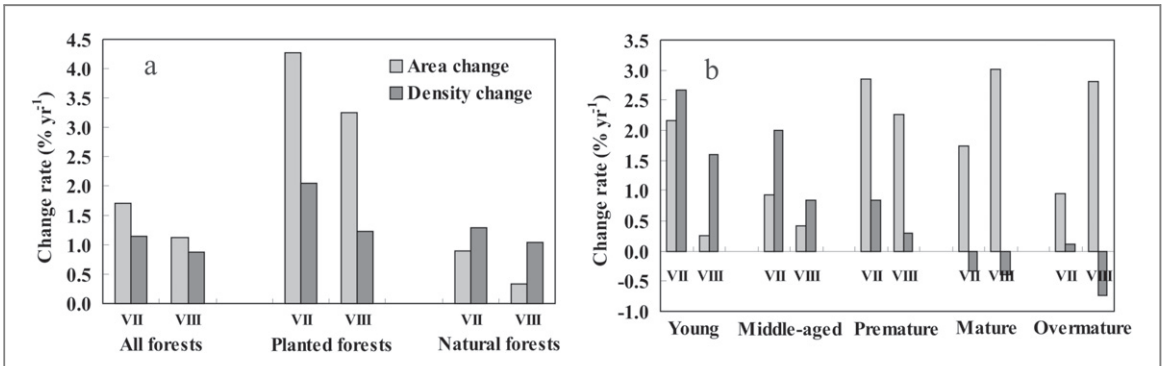

Figure 2. Annual change rates of forest area and biomass carbon density for (a) all forests, planted and natural forests, and (b) five different age classes of forests in China from 2004–2008 to 2009–2013. The numbers of VII and VIII represent two inventory periods of 2004–2008 and 2009–2013, respectively. Negative values indicate decreases in forest area and carbon density and a negative contribution to the national total biomass carbon sink. The data of forest area and biomass carbon density are from table 1 and table S3 (supplementary information).

The north, east, south, and northwest regions exhibited generally similar temporal variations of forest biomass carbon sinks, which decreased during the period from 1977–1981 to 1984–1988 and then gradually increased (figure 3). The decrease was mainly caused by previously intensive harvest of natural and mature planted forests with high carbon density and mostly young planted forests in the deforested areas during 1984–1988 (table S2). Forest biomass carbon sinks in the north and northwest regions increased from 0.4 and 0.6 Tg C yr^{-1} during the period of 1984–1988 to 21.8 and 10.4 Tg C yr^{-1} during the period of 2009–2013, respectively. Due to afforestation and reforestation programs and ecological protection for natural forests, forests in the east and south regions behaved as persistent carbon sinks since 1989–1993. However, forest biomass carbon sinks shrank by 8.1 Tg C yr^{-1} and 19.7 Tg C yr^{-1} in the east and south regions during the period from 2009 to 2013, amounting to 22% and 56% of national total decline of forest biomass carbon sink. In the northeast and southwest regions, forest biomass carbon sinks exhibited bimodal increasing trends during the entire study period. Forests acted as a large biomass carbon

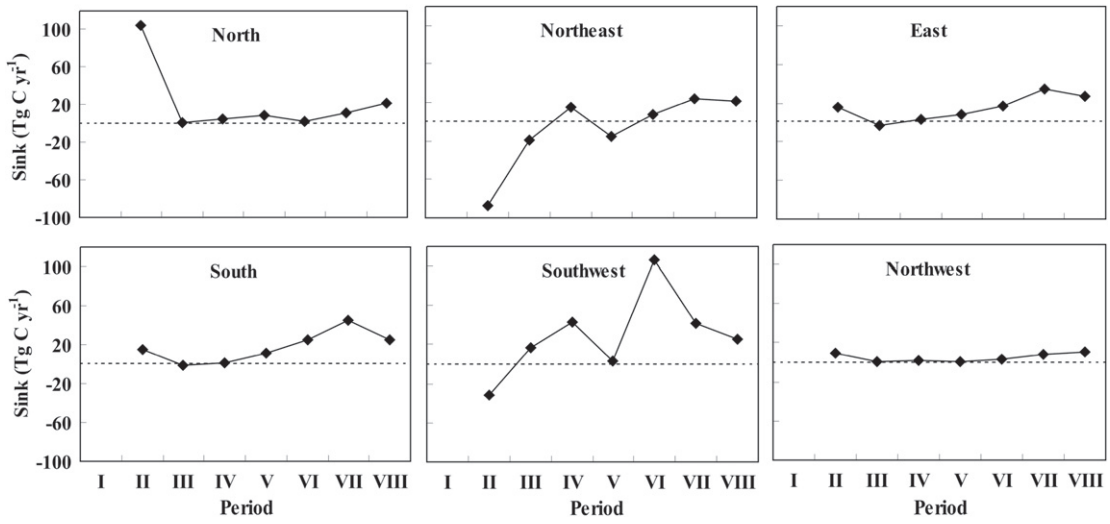

Figure 3. Trends of forest biomass carbon sinks in different regions of China from the period 1973–1976 to 2009–2013. The numbers of I, II, III, IV, V, VI, VII and VIII represent eight inventory periods of 1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008, and 2009–2013, respectively. The negative value indicates a carbon source, and vice versa. Forest geographical regions in China were divided following Fang *et al* (2001).

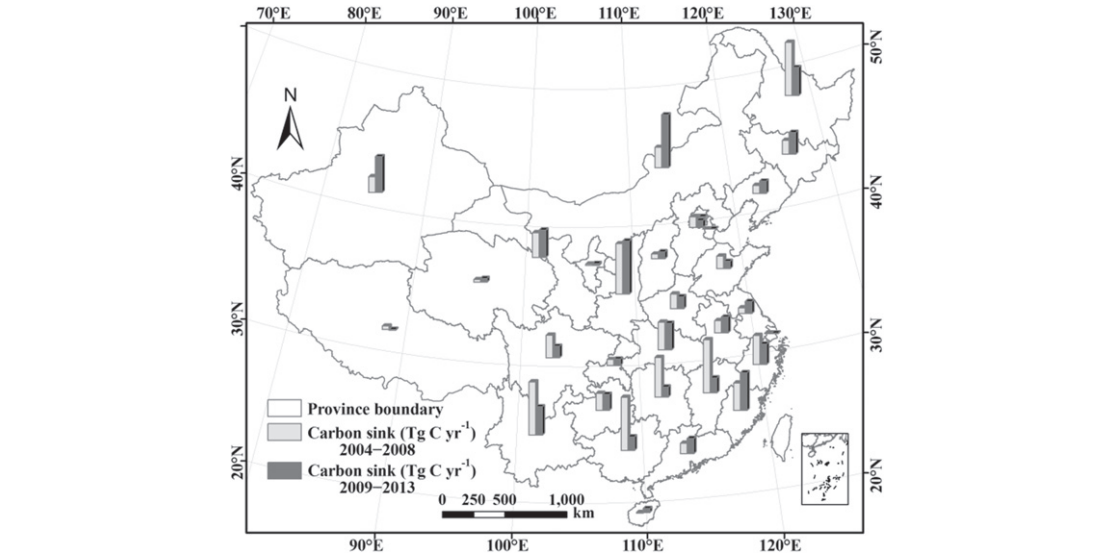

Figure 4. The province-by-province comparisons of estimated forest biomass carbon sink for the two periods 2004–2008 and 2009–2013.

source of 88.0 Tg C yr^{-1} in the northeast region and 31.2 Tg C yr^{-1} in the southwest region during the period of 1977–1981, mainly resulting from extensive timber harvesting of forests (table S1). The largest increase of 106.4 Tg C yr^{-1} in the biomass carbon sink occurred during the period 1999–2003 in the southwest region, contributing to 66% of the national total biomass carbon sink. During the period 2009 to 2013, forest biomass carbon sinks decreased by 3.3 and 16.7 Tg C yr^{-1} in the northeast and southwest regions relative to the biomass carbon sinks during the period 2004–2008, respectively.

During 2009–2013, forest biomass carbon sinks decreased in provinces accounting for 62% of national total forest area (figure 4). The sink reduction occurred mainly in southern provinces, such as Guangxi, Yunnan, Jiangxi, Hunan, Sichuan, Zhejiang, Tibet, Guizhou, and Hubei provinces, with values of 12.4 Tg C yr^{-1}, 10.3 Tg C yr^{-1}, 9.6 Tg C yr^{-1}, 9.2 Tg C yr^{-1}, 4.6 Tg C yr^{-1}, 2.1 Tg C yr^{-1}, 1.7 Tg C yr^{-1}, 0.4 Tg C yr^{-1}, and 0.3 Tg C yr^{-1}, respectively. Heilongjiang province was also a major contributor to the national loss of biomass carbon sinks, where the forest biomass carbon sink decreased by 7.9 Tg C yr^{-1}. During 2009–2013, forest carbon sinks increased in most northern provinces. The largest increase of 10.4 Tg C yr^{-1} in forest biomass carbon sink occurred in Inner Mongolia.

4. Discussion

4.1. Drivers for forest biomass carbon sink reduction during 2009–2013

The drivers for forest biomass carbon sink in China's forests are diverse. The most commonly used indicators for inventory-based carbon sinks are forest area and carbon density (Fang *et al* 2014a). Forests in China acted as a small biomass carbon sink or even a small biomass carbon source during the period of 1973–1998. Then, the forest biomass carbon sink increased significantly to 161.5 Tg C yr^{-1} during 1999–2003 and 166.5 Tg C yr^{-1} during 2004–2008, while it decreased to 130.9 Tg C yr^{-1} during 2009–2013. During the period of 1977–2013, the total national forest biomass carbon sink increased by 105.9 Tg C yr^{-1}, with 66.5 Tg C yr^{-1} and 39.3 Tg C yr^{-1} attributed to planted and natural forests, respectively (table 1).

The largest increase of forest biomass carbon sinks (145.4 Tg C yr^{-1}) occurred during the period 1999–2003, with 95% of this increase contributed by natural forests (table 1). During this period, the biomass carbon sink of natural forests approached 129.5 Tg C yr^{-1}, owing to the concurrent large increases of forest area and biomass carbon density. The biomass carbon sink of natural forests declined to 106.6 Tg C yr^{-1} during the period of 2004–2008 and 73.5 Tg C yr^{-1} during the period of 2009–2013. The decrease of natural forest biomass carbon sink was caused by the simultaneous decreases in the increasing rates of forest area and biomass carbon density. The increasing rate of natural forest area declined even more than that of biomass carbon density of natural forests (figure 2(a)). Starting from 1989, the biomass carbon sink of planted forests continuously increased and approached 59.9 Tg C yr^{-1} during the period of 2004–2008 and then slightly decreased to 57.4 Tg C yr^{-1} during the period of 2009–2013. The contribution of planted forests to the national total biomass carbon sink was 20%, 36%, and 57% during periods of 1999–2003, 2004–2008, and 2009–2013, respectively. The increase in biomass carbon sink of planted forests was mainly driven by the increase of area, from 29.14×10^6 ha during the period of 1994–1998 to 47.07×10^6 ha during the period of 2009–2013. Meanwhile, biomass carbon density increased from 22.5 Mg C ha^{-1} to 29.7 Mg C ha^{-1} (table 1, figure S1).

The reduction of forest biomass carbon sinks in China during 2009–2013 was not caused by a decrease in afforestation area, as the total area of newly planted forests increased by 7.52×10^6 ha during period from 2004–2008 to 2009–2013 (Chinese Ministry of Forestry 2013). The 12.67×10^6 m^3 increase of timber harvest (figure 5), approximately equal to 5.91 Tg C of biomass loss (it was calculated on the basis of harvested timber volume and provincial average coefficients converting timber volume into biomass Zhang *et al* 2013), was the main driver for the decline of forest biomass carbon sink during the period of 2009–2013. Timber harvest has the highest correlation with biomass carbon sink among all types of disturbances (table 2). In general, the biomass carbon sink size and harvesting intensity are negatively correlated at different scales of China, with the regression slope and correlation coefficient values were respectively −0.85 and −0.68 for 31 provinces ($p < 0.01$) and −1.07 and −0.84 for six regions ($p < 0.05$) (figure S2). During the period of 2009–2013, less deforestation and forest growth in the north and northwest regions dominated the increase in biomass carbon sinks. Meanwhile, in other regions, the biomass carbon sink reduction was largely caused by more intensive deforestation, and young ages of forests in most deforested areas during 2009–2013.

The magnitude of forest biomass carbon sinks not only depends on forest area, but is also related to forest age structure (Ciais *et al* 2008, Pan *et al* 2011, Xu *et al* 2012). Changes in forest age-class structure can result in prominent changes in the rates of carbon sequestration and emissions (Kurz *et al* 2008). Afforestation, deforestation, and reforestation have significantly modified the age structure of forests in China. Currently, forests were dominantly young and middle-aged stands with the area proportion ranging from 65% to 72% during 1973–2013 (figure 1(a)). In this study, it was found that the biomass carbon sink strength increased first with stand ages followed by a decrease during most inventory periods, and peaked at middle ages of stands. Mid-age forests generally sequester carbon at higher rates than mature forests. A carbon source for young forests during 1989–1998 was attributed to relatively small stand ages of planted forests. Forests in other age classes acted as carbon sources mainly because of deforestation (table S3). After 1999, young forests acted as a carbon sink owing to the rapid increase of forest area and timber harvest volume (table S1). Young, middle-aged, and premature forests together contributed to 71%, 85%, and 61% of national total forest biomass carbon sinks during the periods of 1999–2003, 2004–2008, and 2009–2013, respectively. Mature and overmature forests played minor roles in the national total biomass carbon sink during the period of 2004–2008. During the period of 2009–2013, the large reduction of national total biomass carbon sink was primarily caused by biomass changes in young and middle-aged forests, which experienced increasing harvest (table S3). For mature and overmature forests, less deforestation and forest regrowth were dominant causes of the carbon sink increase during this period (Chinese Ministry of Forestry 2014). However, the increase in biomass carbon sinks of mature and overmature forests was unable to compensate for the large biomass carbon sink reduction of young and middle-aged forests caused by extensive deforestation, especially in the east and south regions, in which young and middle-aged forests occupy a dominant proportion (figure 3).

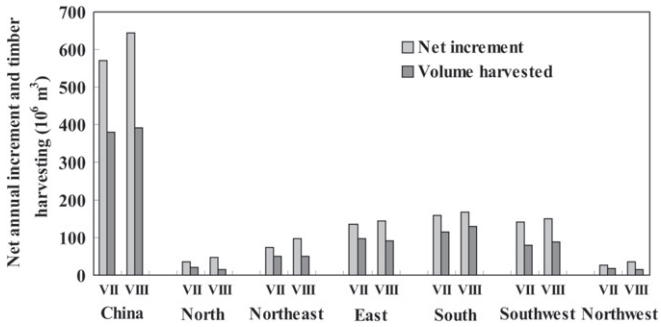

Figure 5. Volume of net annual increment and timber harvested for forests in different regions of China during the two periods of 2004–2008 and 2009–2013 (Chinese Ministry of Forestry 2009, 2014). Net volume increment is defined as the average annual volume of gross increment over a given period minus the average annual volume of natural mortality of trees. The numbers of VII and VIII represent two inventory periods of 2004–2008 and 2009–2013, respectively.

Table 2. Pearson correlation coefficients between changes in biomass carbon sinks during the period of 2009–2013 relative to the values during the period of 2004–2008 with respective changes of harvested stand volume and forest areas affected by natural disturbances retrieved from the national forest inventory data at different scales (Chinese Ministry of Forestry 2009, 2014).

Scale	Harvest	Natural	Diseases	Insects	Fire	Windthrow	Snow	Landslide	Drought	Others
Province	−0.676[b]	−0.447[a]	−0.224	0.185	0.219	−0.256	−0.554[b]	0.560[b]	−0.316	−0.187
Region	−0.836[a]	−0.2000	0.169	0.635	−0.377	0.068	−0.698	0.558	0.224	−0.283

[a] Correlation is significant at the 0.05 level (two-tailed).

[b] Correlation is significant at the 0.01 level (two-tailed).

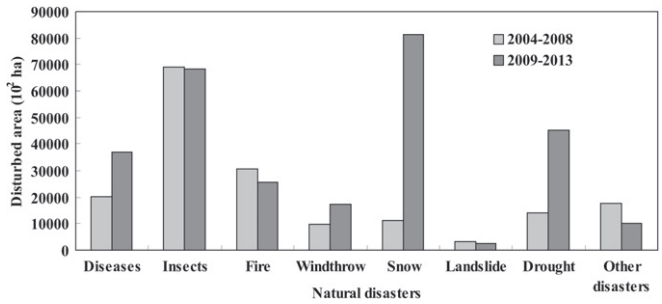

Figure 6. Forest areas disturbed by different types of natural disturbances during periods of 2004–2008 and 2009–2013 in China (Chinese Ministry of Forestry 2009, 2014).

Increased timber cutting and slow forest regeneration were main drivers for the biomass carbon sink reductions of all age classes of forests in the southwest region (figure S3).

Forest biomass carbon sinks are vulnerable to natural disturbances (Kurz *et al* 2008, Nabuurs *et al* 2013, Espírito-Santo *et al* 2014) and climate extremes, such as drought (Zhao and Running 2010, Van der Molen *et al* 2011, Schwalm *et al* 2012). According to national forest resource statistics, the total forest area disturbed by eight different types of natural disasters during the period of 2009–2013 increased by about 63% relative to the value during the period of 2004 to 2008. Snow damage was the largest contributor to this large increase in naturally disturbed-area (63%), followed by drought (28%), diseases (15%) and windthrow (7%) (figure 6). These disturbances in combination with increased harvest caused forest biomass carbon sinks to decrease in China. This conclusion is supported by the negative correlation coefficients between changes in biomass carbon sinks during the period of 2009–2013 relative to the values during the period of 2004–2008 with respective changes in harvested stand volume and forest areas affected by natural disturbances (table 2). Such disturbance-induced reduction of biomass carbon sinks occurred mainly in east, south, southeast, and southwest regions (table S4). Area of damage caused by other four types of natural disturbance slightly decreased during the period of 2009–2013 (figure 6). Various disturbances affected forest biomass carbon sinks differently. The damage caused by the extreme snow event in the winter of 2008 was recorded in the 2009–2013 inventory since the field campaign of 2004–2008 inventory already finished at that time. The most common form of snow damage to forest stands is stem breakage or bending.

Damaged stems increased the amount of natural losses (table S4) and weakened stand growth, resulting in the decrease in carbon sequestration by forests. In addition to recorded lag of snow damage data, another major reason for the reduction in biomass carbon sink may be the lagged effect of snow damage in southern provinces (including Guangxi, Jiangxi, Hunan, Guizhou, Hubei, and Zhejiang) of China (Sun *et al* 2012, Wang *et al* 2014). The snow-induced decrease in carbon sink was definitely responsible for the sink reduction in the east and south regions, because the decrease of the carbon uptake was well consistent with the increase of snow damage in major forest provinces of these regions (table S4). A similar conclusion has been indicated by previous studies (Zhang *et al* 2011, Huang *et al* 2013). The primary immediate responses of forests to drought are to reduce leaf area, biomass increment and water use efficiency, which are driven by drought- and heat-related physiological stress and mortality (Martínez-Vilalta *et al* 2012, Ma *et al* 2012, Law 2014, Liu *et al* 2014). This may explain a large sink reduction in Yunnan province of the southwest region because several severe and sustained drought events occurred here (Zhang *et al* 2012b, Liu *et al* 2014). In addition to excessive deforestation, high fire disturbance may be another important factor driving the sink reduction in Sichuan province. Drought, diseases and windthrow damages to forests occurred mainly in Heilongjiang province (table S4). Their combined effects weakened the carbon sink strength in this province.

4.2. Uncertainties and limitations

This study was conducted using the CBEF method, which was firstly developed by Fang *et al* (2001) and refined by Zhang *et al* (2013), and 8 inventory datasets. It tried to explore the possible drivers for biomass carbon sink reduction of China's forests in recent years. Biomass carbon sink estimated using the CBEF model is very sensitive to model parameters (Zhang *et al* 2013). With the refined CBEF model parameters, the estimates of forest biomass carbon sinks could be improved in comparison with previous studies (Zhang *et al* 2013). It definitely still contains some uncertainties. The carbon sink was estimated using the refined empirical relationships between volume and biomass, which were developed using available field measurements (3543 plots). The estimation error might reach about 10% if the number of samples used to establish a biomass model for a forest type is inadequate (Smith *et al* 2002). We tried to collect almost all data published in recent decades in China. The number of plots for some forest types (such as *Phoebe*, *Sassafras*, and *Acacia*) is still too small (Zhang *et al* 2013). In addition, the field data might be collected with different methods, dates, and plot sizes. Uncertainties in field biomass data might induce errors in carbon sink estimation.

The criteria of canopy coverage for forest changed from 30% to 20% in 1994. The area and biomass stocks during the period of 1973–1998 were empirically corrected. The uncertainties in biomass carbon stocks for the period of 1994–1998 might propagate into the estimated biomass carbon sinks for the period of 1999–2003. Over the whole study period, the biomass carbon sink maximized during the period of 2004–2008. A similar conclusion was recently reported by Guo *et al* (2013). Increased timber harvest and natural disturbances combined to cause the sink reduction during the period of 2009–2013. Using a process-based ecological model driven by remotely sensed vegetation parameters, Liu *et al* (2014) declared that drought weakened carbon sequestration by forests in China during the period of 2004–2011. Our estimated changes of provincial biomass carbon sinks during the period of 2009–2013 relative to the values during the period of 2004–2008 were in significant agreement ($p < 0.01$) with corresponding changes of provincial total annual NPP simulated by Liu *et al* (2014) (figure S4).

Our findings indicated that increased harvest and natural disturbances, such as droughts, snow, disease, and windthrow, are important perturbation factors causing the reduction of biomass carbon sinks. Droughts and ice storms occurred in recent years substantially reduced NPP and the biomass carbon increment of forests in disaster-stricken areas, such as Yunnan (Zhang *et al* 2012b), Jiangxi (Wang *et al* 2014), and Hunan (Sun *et al* 2012) provinces. Furthermore, forest cutting activities exert significant impacts on the carbon cycle in these areas. Planted young forests are vulnerable to disturbances, such as deforestation and extreme climatic events (Huang *et al* 2013). The recent large reduction in biomass carbon sink of young forests in China was caused by the integrated effects of increased timber harvesting and a number of natural disturbances. However, it is difficult to quantify the roles of different disturbance factors in inducing biomass carbon sink reduction due to data limitation.

Natural and human-induced forest disturbances have been identified as critical factors regulating biomass carbon sink dynamics. Previous studies concluded that recent decreases in forest growth, NPP, and carbon sequestration in China are largely due to the effect of climate-induced severe climatic events based on model simulations (Pei *et al* 2013, Liu *et al* 2014), *in situ* eddy covariance flux data (Huang *et al* 2013) and field biomass measurements (Wang *et al* 2014). However, these studies did not well examine the effects of anthropogenic disturbances, such as forest cutting, on biomass carbon uptake by forests at national and regional scales. Here, the combined impacts of anthropogenic and natural disturbances on forest biomass carbon sinks were assessed using long-term forest inventory data. Owing to the lack of information on the amount and spatial distribution of different types of forest disturbances and associated

changes of forest biomass carbon stocks, the reduction of biomass carbon sinks caused by disturbances was only assessed at the provincial and regional levels based on statistical data. The contribution of individual disturbances were unable of estimate quantitatively. The indirect effects of disturbances, such as disturbance interactions and lagged effects of disturbances, might also drive the variability of forest biomass carbon sink and were not analyzed in this study.

4.3. Implications for forest biomass carbon sinks in China

The refined estimates of forest carbon sinks in China can contribute to understanding the dynamics of the terrestrial carbon cycle and underlying mechanisms. Our results suggest that, within the limits of reported uncertainties, the national biomass carbon sink continuously increased between 1989 and 2008, and then substantially decreased for the period of 2009–2013. Over the period of 2004–2013, the forest biomass carbon sink in China averaged 148.7 Tg C yr^{-1}, approximately equal to 6.7% of the contemporary fossil-fuel CO_2 emissions in China. If the sinks of four other carbon pools (dead wood, litter, soil organic carbon, and harvested wood products) were also taken into account, the whole forest sector could act as a carbon sink of about 235.3 Tg C yr^{-1} using the ratios of different carbon pools in China's forests following Pan *et al* (2011). This forest carbon sink could offset 10.6% of the national CO_2 emissions from fossil-fuel combustion. Recent biomass carbon sink reduction indicates that suitable measures are imperative to maintain and to enhance this valuable forest carbon sink for mitigating the increase of CO_2 emissions from deforestation and fossil-fuel combustion in China.

A large carbon uptake in China's forests is directly associated with areal expansion and increased carbon density from afforestation and reforestation, natural forest conservation, and the Green for Grain programs. According to Forest Resource Statistics of China 2009–2013 (Chinese Ministry of Forestry 2014), the quantity and quality of forests in China have stepped into a steady development stage, implying that the potential for the increase of biomass carbon sinks might be limited. The total wasteland area currently available for forest development in China is only 0.39×10^8 ha (about half preserved plantation area) (Chinese Ministry of Forestry 2014). About two third of these wastelands is located in the vast northwest and southwest regions, where plantations are limited by cold or drought conditions and have low survival rates. Therefore, gaining new carbon through forestation in the future might become more difficult.

Stand age is a major determinant of the carbon sink or source strength in forest ecosystems. Age-related carbon sink changes have been extensively discussed (Liu *et al* 2012, Wu *et al* 2014, Yu *et al* 2014). It was found here that forests shortly after disturbance events, such as afforestation, reforestation, and deforestation, often act as carbon sources. This conclusion is consistent with previous studies (Pan *et al* 2011, Zhang *et al* 2012a, Deng *et al* 2013). The rapid quantity and quality increases of forests through afforestation and reforestation, and effective forest management practices in recent decades made different age-class forests function as carbon sinks and a majority of forests are in the young and middle-aged classes in China. Middle-aged and mature forests have high biomass carbon density and sink strength (table S1). If existing young and middle-aged forests could evolve into mature forests, considerable amounts of carbon can be absorbed by forests in China. Therefore, increasing forests productivity would be a more effective method for carbon sink maintenance and enhancement in the coming decades.

The considerable reduction of biomass carbon sinks during the period of 2009–2013 was largely induced by disturbances. With recovery of forests, this loss carbon sink might be regained. Generally, forests regenerating after disturbances tend to accumulate carbon over the long term, although they often act as a carbon source immediately after disturbances. For example, it has been found that forest recovery after fires, afforestation and reforestation were the most important contributor to the increase of forest biomass from 2001 to 2010 in Northeastern China (Zhang and Liang 2014). In this study, the biomass carbon sink of China's forests was found to decrease during the period of 2009–2013 based on national inventory data, which integrate the effects of various forest disturbance factors. The decrease of biomass carbon sinks was basically synchronous with or slightly lagged the increase of forest disturbances. Without extensive disturbance, widely distributed young forests with high potential of carbon sequestration in China might continuously enhance carbon sinks in the future. The intensity of timber harvest greatly influences the biomass carbon sink through decreasing forest area directly. Selective cutting with proper harvest intensity is an effective measure to improve forest growth. Recently increasing severity and incidence of climatic extremes, including drought and snow storm, reduced the forest carbon sink through suppressing GPP and increasing fires, insect damage, and tree mortality. Forests damaged by these disturbances might recover carbon sequestration in the future. The complex effects of forest disturbances and successive growth patterns on the carbon cycle of China's forests should be thoroughly investigated.

5. Conclusion

In this study, the dynamics of biomass carbon sinks for China's forests were systematically assessed using eight inventory datasets from 1973 to 2013 and a refined CBEF model. The drivers of recent carbon sink

reduction in different regions were explored. Following conclusions can be drawn:

(1) The national biomass carbon sink increased from 25.0 to 166.5 Tg C yr^{-1} between 1973 and 2008, and then decreased to 130.9 Tg C yr^{-1} for the period of 2009–2013. Forests in China functioned as an average biomass carbon sink of 80.6 Tg C yr^{-1} over the last four decades. About 63% and 37% of sink increase were contributed by planted and natural forests, mainly driven by area expansion and forest growth.

(2) The slowdown in the increases of forest area and biomass carbon density were the direct causes for the carbon sink reduction from 2004 to 2013. Natural forests contributed 93% of this sink reduction. The carbon sinks of young, middle-aged and premature forests decreased by 27.3, 27.0, and 7.6 Tg C yr^{-1}, respectively, during this period. Increased carbon sinks of mature and overmature forests compensated for 42% of sink reduction of younger forests.

(3) Forest carbon sinks decreased in all regions except the north and northwest regions during the past decade. Increased harvest for young and middle-aged forests and snow damage were the major contributors to the carbon sink reduction in the east and south regions. Enhanced timber harvesting and natural disturbances (including drought, forest fires, and snow damage) were largely responsible for the sink reduction in the southwest region. In the northeast region, the combined effects of diseases, windthrow and drought dominated the sink reduction.

This study updates current estimates of the biomass carbon sink in China's forests. Our results provide new insights to the characteristics of forest carbon sink reduction in recent years and highlight the significance of forest disturbances in regional and national carbon balance. They would be a basis for comprehensive investigations of the forest carbon budget and underlying mechanisms.

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